Cold Spray Coatings for Prevention and Mitigation of Stress Corrosion Cracking

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Addressing Nuclear Concerns

- Austenitic Ni and Fe alloys comprise the bulk of wetted surfaces in nuclear power plants
- These alloys are susceptible to stress corrosion cracking (SCC) especially after extended service life
- Repair and mitigation of components in the field is difficult and costly
- A cost-effective field-deployable methodology to protect the affected surfaces is desired
- Cold Spray offers tremendous advantages in preventing SCC from initiating, and repair of existing affected areas

Cold Spray Advantages for Nuclear Applications

- No heat affected zone
- Wrought, not cast, structure
- Compressive surface layer
- Minimal surface preparation required
- Machines like normal metal
- High adhesion (>10 ksi)
- Can be easily applied using robotics
- Surface is <u>inspectable</u> with PT and UT*

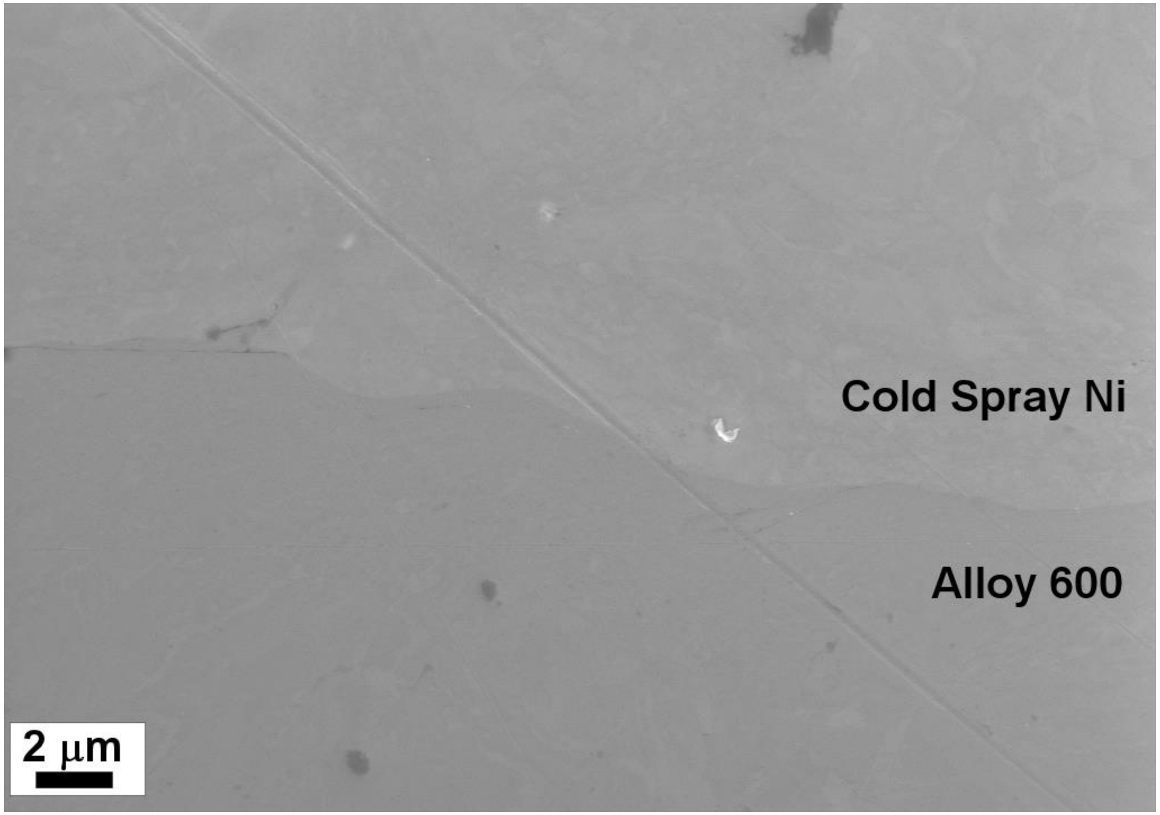
*without an inspectable coating, all other attributes are academic

Cold Spray Nickel

- Nickel is much more resistant to SCC at primary water conditions than austenitic alloys
- Nickel comprises ~70% of wetted non-fuel surface area in the plant
- It is isotropic, homogeneous, and doesn’t have any secondary phases
- Nickel is available commercially as a high purity cold-sprayable powder

The Ni-Alloy 600 Interface

The coating is as good as the interface



Note the clean, well-bonded interface and pore-free coating

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Tests Completed

To determine the efficacy of the coating for primary water applications, the test program encompassed the following:

- Coating morphology (cross-section, roughness)
- Mechanical properties (fatigue, ductility, adhesion, etc.)
- Inspectability (UT and PT)
- Ability to protect against SCC (halide/sulfate doped steam)
- Coating complex surfaces

Testing conducted over 18 months on 200+ various specimens

Mechanical Testing

- Ductility
  - – Ductility of as-deposited Ni >2.25% strain
- Hardness
  - – Vickers performed on polished x-section of coating, showed remarkable consistency in hardness (~260 VHN)
- Adhesion
  - –Specimens bent 180° over a mandrel three times and flattened
  - –Coating cracked but did not spall or disbond
- Cyclic Fatigue
  - – 4-point fatigue, 50000 cycles, 22.5 ± 21 ksi tensile stress load
  - – UT, PT and SEM showed no coating cracking or disbonding
- Thermal Cycling
  - – Heated to 400 °C and plunged in water for 100 cycles
  - – UT, PT and SEM showed no coating cracking or disbonding
- Impact Testing
  - – Coating struck with a round-nosed weight with 10J energy and showed no cracking or spalling

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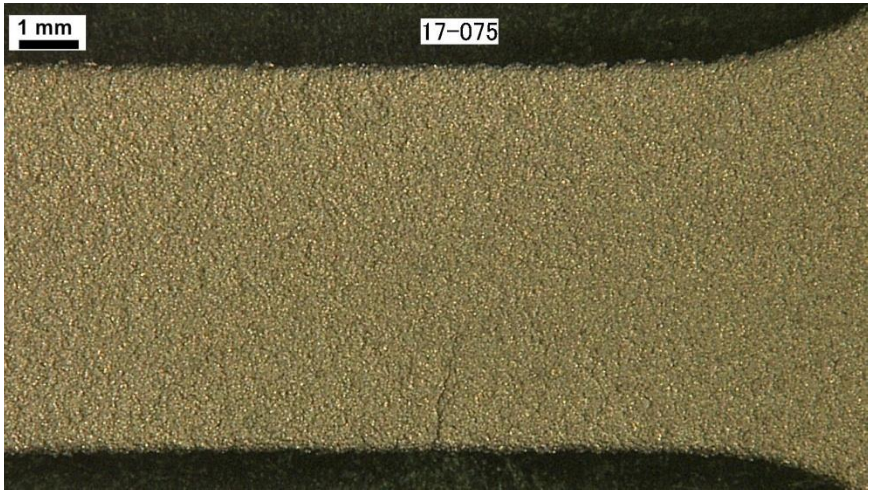
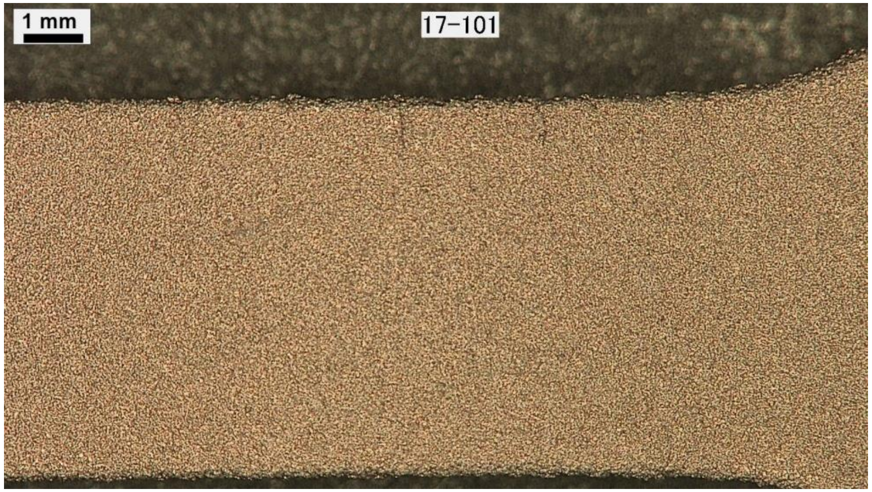
Coating Ductility



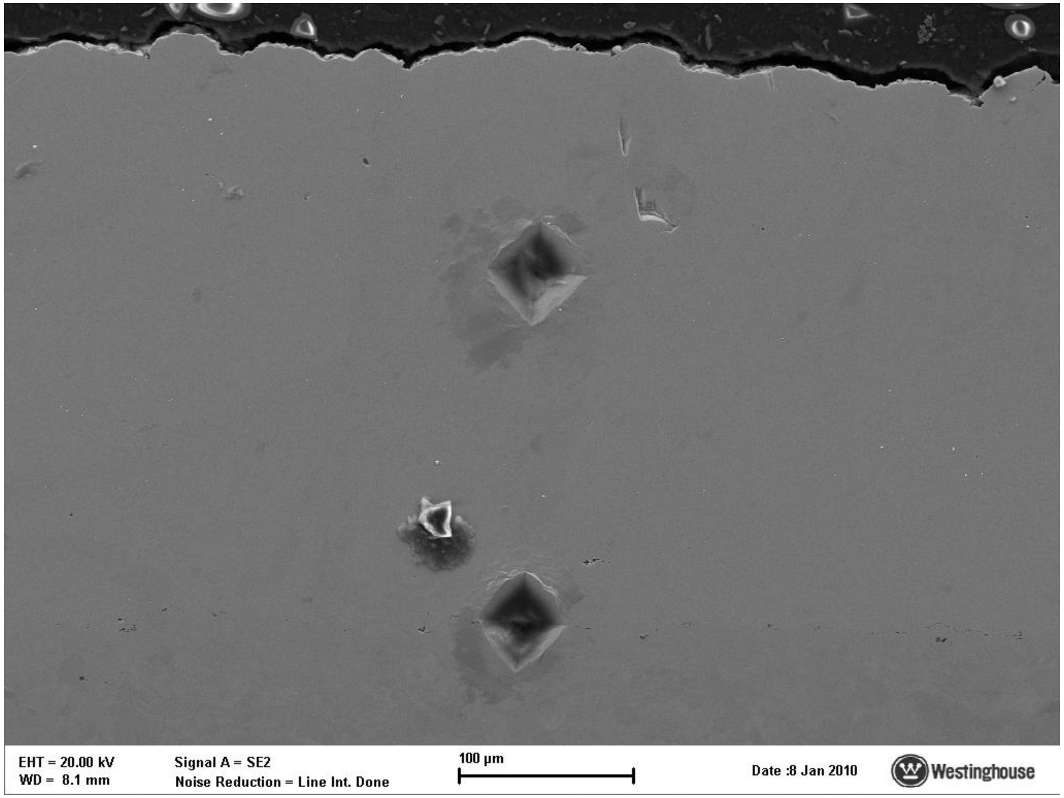
25 °C



270 °C

- Room temperature cracking observed at ~2.25-2.5% strain
- At 270 °C, cracking is observed at 8-9% strain
- At 350 °C, no cracking observed up to 16%

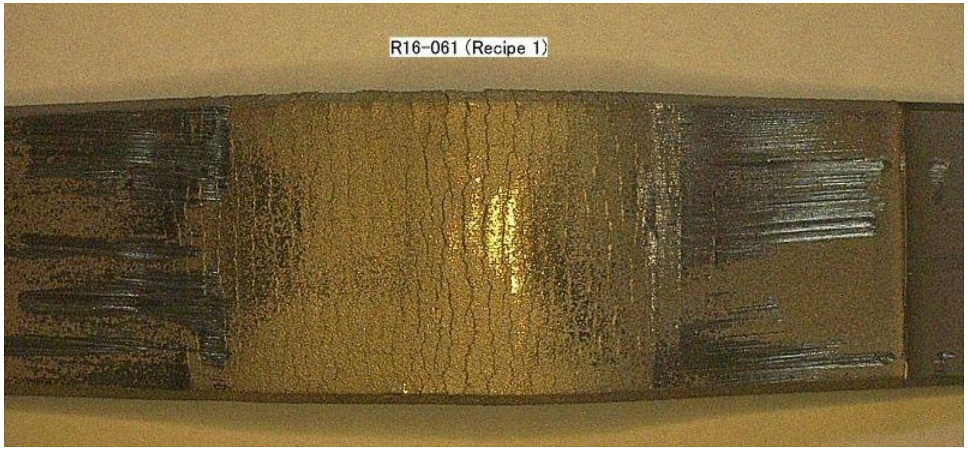
Cross-Section Vickers Hardness

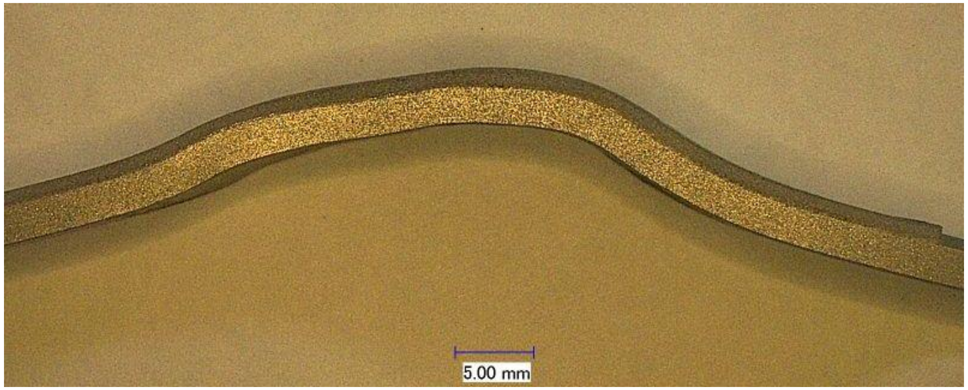


CS Ni Coating: 264 ± 9 VHN
Alloy 600 Substrate: 175 ± 7 VHN

Adhesion Strength by Bending

- Bend bars bent 180° around a mandrel and flattened 3 times
- Coating cracks but remains adhered over the entire surface
- No delamination from the Alloy 600 substrate





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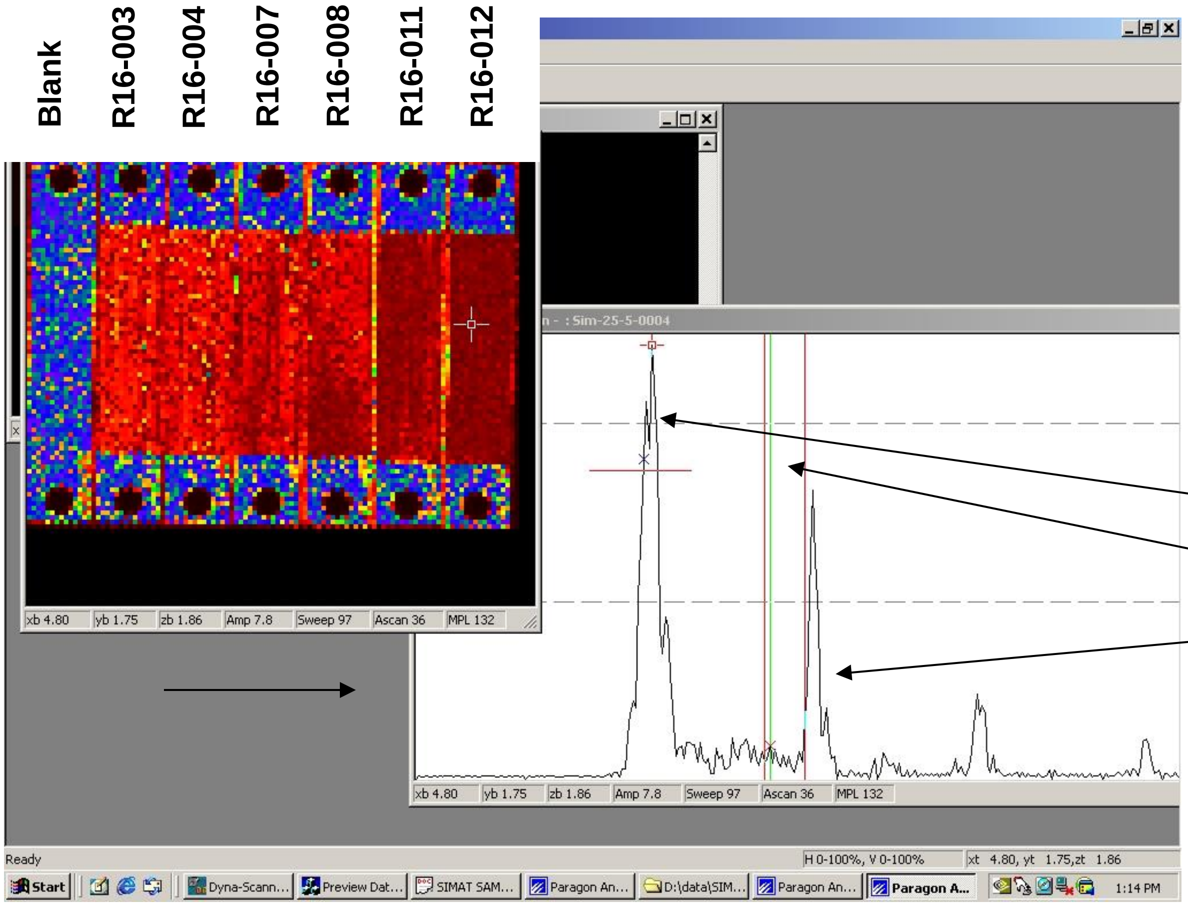
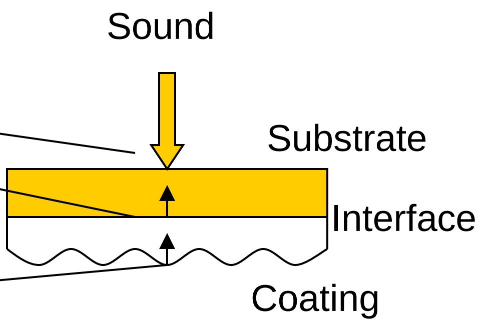
UT Inspection

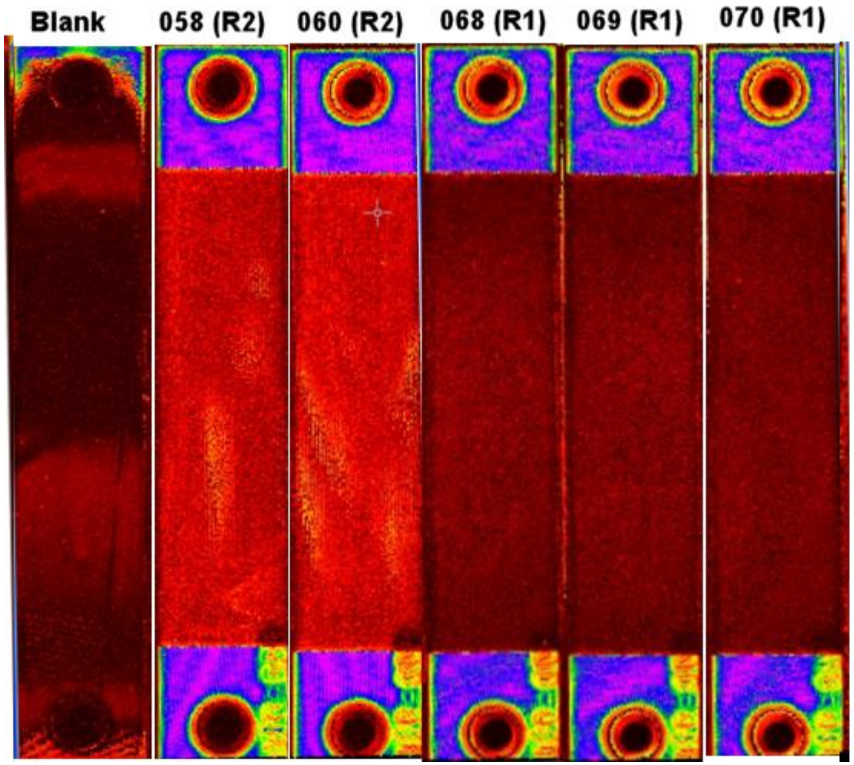


Inspection
Frequency – 25 MHz



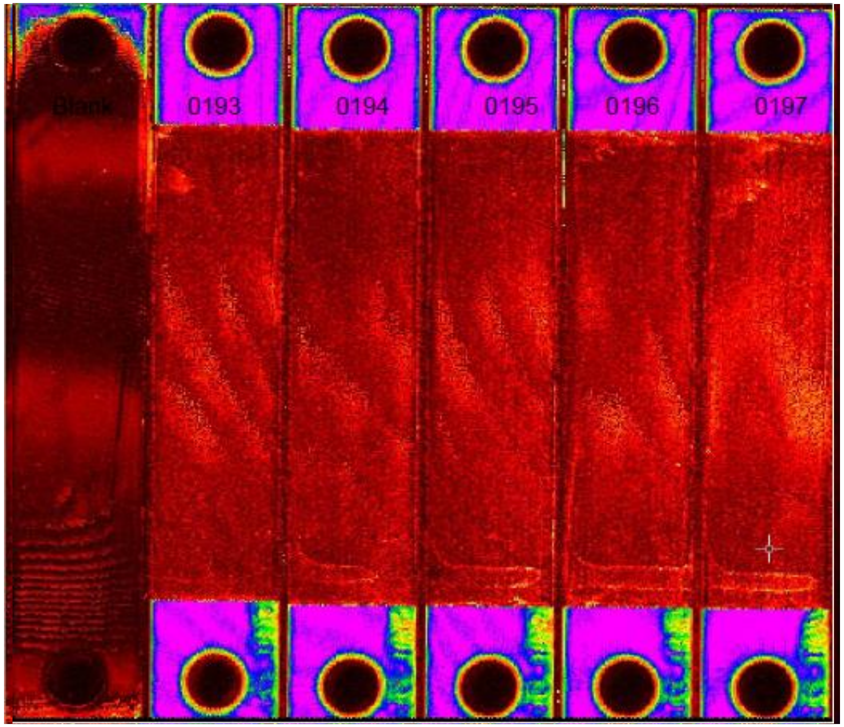
Fatigue

- 4-point fatigue testing to determine coating behavior under cyclic loads
- 50,000 cycles, mean tensile stress of 22.5 ksi (50% of yield) and stress amplitude of ±21.7 ksi



Thermal Cycling

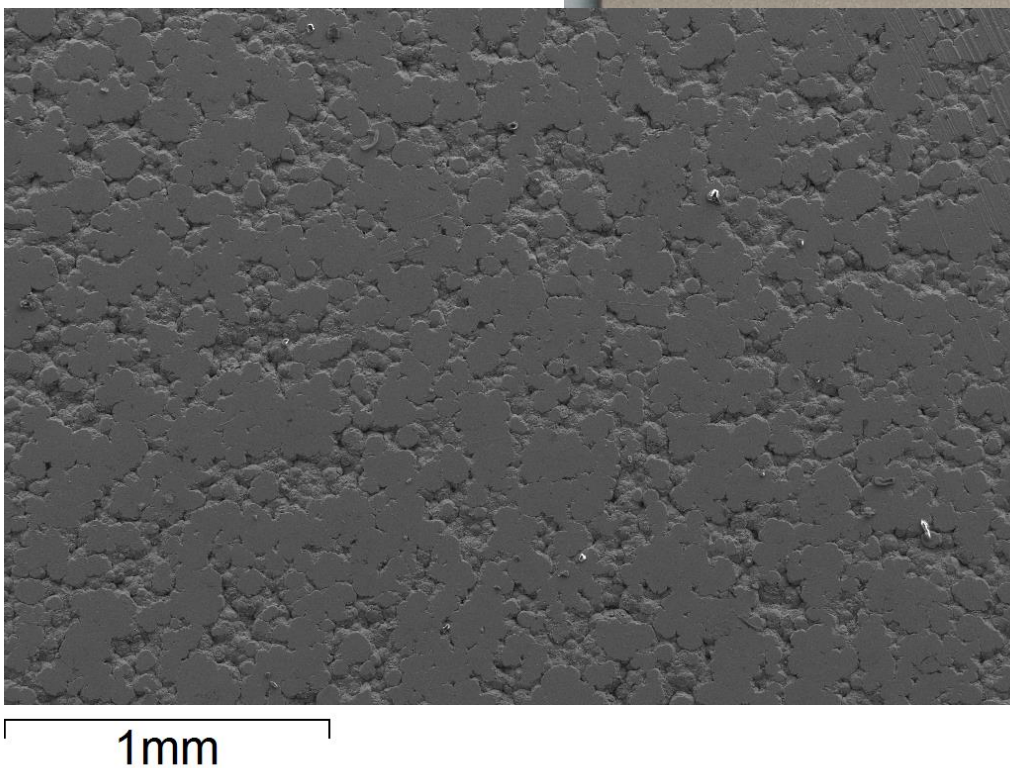
- No change in UT signal for any sample, indicating a tightly adherent coating which is not susceptible to thermal shock

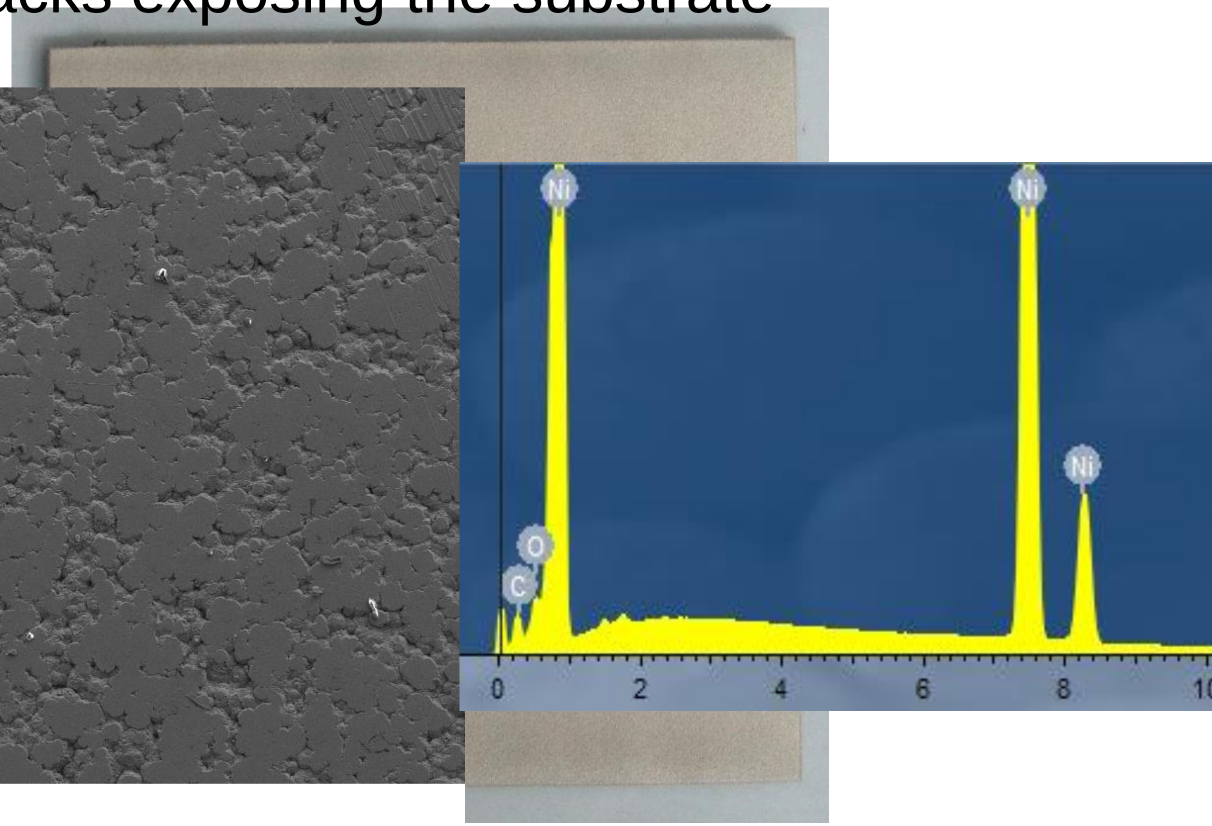


After 5 days
After 100 cycles

Impact Testing

- Surface struck with a hemispherical weight delivering 10 J of energy (courtesy of ARL)
- Surface characterized by SEM/XEDS to determine the presence of any cracks exposing the substrate





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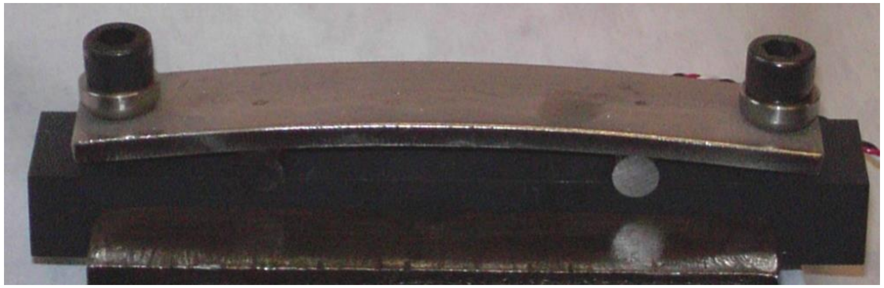
Doped Steam SCC Testing

• Testing performed on strain-hardened 1/8” thick and 1/4” thick Alloy-182 clad bend bars

• Fully and partially coated specimens tested

• Specimens cyclically strain-hardened, and stressed to 70, 75 and 80 ksi tensile

• Corrosion testing carried out at 750° F, 5-13 psia H_2, 80 ppm of F^-, Cl^- and SO_4^{2-}



Doped Steam SCC Testing

- 1/8” Alloy 600 bend bars: control specimens cracked within 200 hours, coated specimens did not crack (1000 hrs total testing)
- ¼” Alloy 182-clad bend bars: control specimens cracked within 200 hours, coated specimens did not crack (800 hrs total testing)
- Doped steam testing accelerates onset of SCC by >300 x, suggesting that cold spray Ni can protect Alloy 600 > 34 yrs*

(*) Materials Reliability Program: An Assessment of the Control Rod Drive Mechanism (CRDM) Alloy 600 Reactor Vessel Head Penetration PWSCC Remedial Technique (MRP-61), EPRI, Palo Alto, CA: 2003.1008901.

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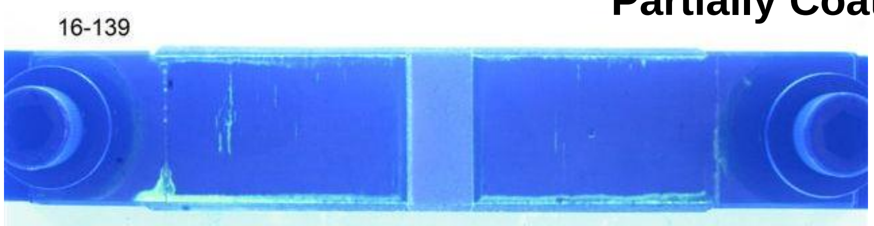
Doped Steam SCC Testing

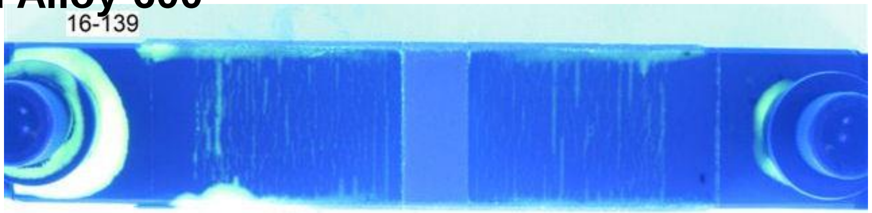
After 200 hrs | After 1000 hrs

Uncoated Alloy 600

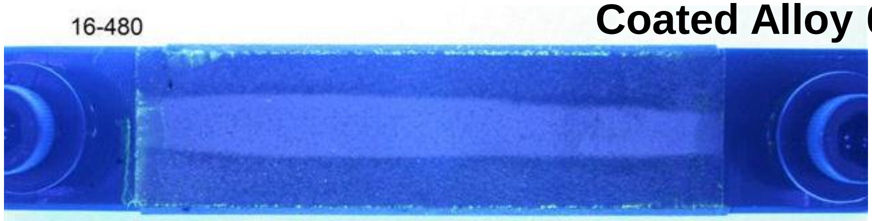
Coated Alloy 600

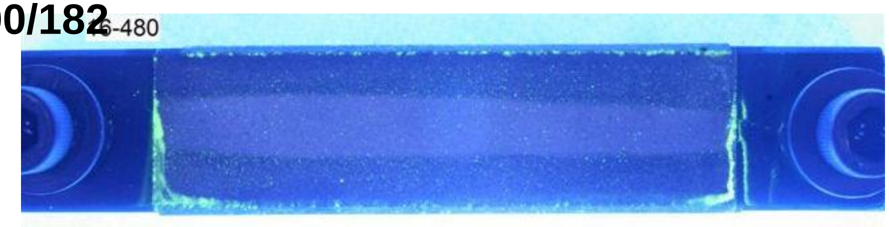
Partially Coated Alloy 600





Coated Alloy 600/182





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Stainless Steel Pipe Coating

- 360° band, 3” wide, shown as coated with no post surface preparation
- Coated with oxide removed (“Blasted”) and as received (“Oxidized”)
- “Pipe over a pipe” increases burst strength

Carbon Steel Plate with Excavation

- 30% of wall machined away to simulate corrosion, oxide removed
- UT show strong bond
- Surface finished with hand held flapper wheel

Summary

• Successful application of pure Ni coating using Cold Spray on Alloy 600 for SCC mitigation

• Mechanical tests show the recipes to be sufficiently ductile for intended application and very resilient (fatigue, thermal cycling, impact, etc.)

• Doped steam tests show the Ni coatings protect substrate against SCC for an extended period of time

• Cold Spray shows great promise in corrosion mitigation for very demanding applications